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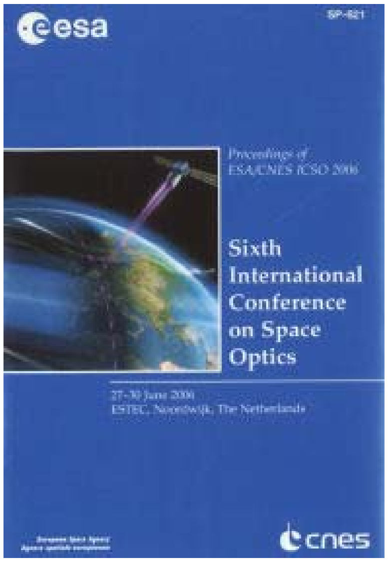

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Novel concept for a 0.5-j laser pump source with high electro-optical efficiency

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NOVEL CONCEPT FOR A 0.5-J LASER PUMP SOURCE WITH HIGH ELECTRO-OPTICAL EFFICIENCY

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ABSTRACT

Future LIDAR and range-finding missions in space require high-energy pulsed lasers. Typical concepts require a pump laser in the NIR spectral range, which is frequency-converted to the requested wavelength by external measures. We propose a novel master-oscillator power-amplifier (MOPA) concept capable to deliver 500-mJ pulses of about 10 ns pulse width at a pulse repetition frequency of 100 Hz. The output at 1064 nm is single-frequency, linearly polarized, and exhibits high beam-quality.

Key words: laser, pumping, efficiency, high energy.

1. INTRODUCTION

For space-based lasers, high electro-optical (eo) efficiency is a key design driver. When building high-efficiency lasers, usually a compromise between efficiency, beam quality, and output power has to be found. Optimisation of all three parameters becomes even more difficult for Q-switched lasers with high pulse energies, mainly due to intra-ion loss mechanisms and parasitic oscillation.

To build a high-efficiency space-based laser, some general aspects have to be taken into account. The laser should have very low thermo-optical aberrations, since aberrations reduce the extraction efficiency for high beam quality laser modes. Furthermode, the overlap between the gain distribution and the laser mode should be high, in order to completely extract the stored energy. To make the laser rugged and compact, only a minimum of pump beam shaping should be required. In the case of high energy storage, the inversion distribution should be homogeneous, in order to avoid inversion hot spots and thermo-optical aberrations. Due to the temperature-dependent wavelength drift of laser diodes, the absorption pathlength inside the crystal should be long enough to compensate for a varying pump absorption coefficient. Finally, amplified spontaneous emission (ASE) and parasitic oscillation (PO) need to be reduced.

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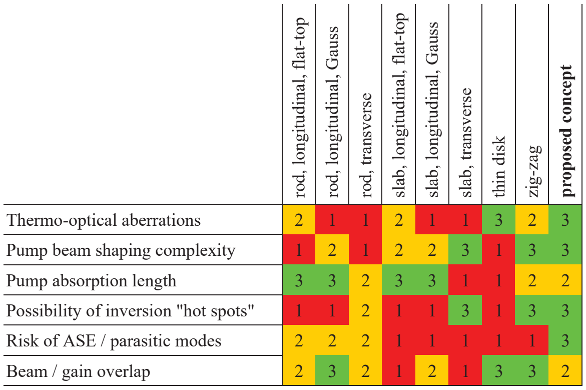

	rod, longitudinal, flat-top	rod, longitudinal, Gauss	rod, transverse	slab, longitudinal, flat-top	slab, longitudinal, Gauss	slab, transverse	thin disk	zig-zag	**proposed concept**
Thermo-optical aberrations	2	1	1	2	1	1	3	2	3
Pump beam shaping complexity	1	2	1	2	2	3	1	3	3
Pump absorption length	3	3	2	3	3	1	1	2	2
Possibility of inversion "hot spots"	1	1	2	1	1	3	1	3	3
Risk of ASE / parasitic modes	2	2	2	1	1	1	1	1	3
Beam / gain overlap	2	3	2	1	2	1	3	3	2

Figure 1. Laser concept comparison for 1064-nm lasers with high pulse energy

Figure 1 shows a rough classification of common laser concepts with respect to the requirements mentioned above. The properties of the different laser concepts are color-coded and graded with 1 to 3 points. Green indicates the most favorable properties and corresponds to 3 points. Yellow (2 points) indicates an intermediate property and red (1 point) indicates a poor property of a laser concept. "Longitudinal" and "transverse" refer to the pump beam direction, while "flat-top" and "Gauss" refer to the intensity distribution. The laser mode is always assumed to be TEM_{00}.

Most slab or rod geometries suffer from a heat extraction in a direction transverse to the laser beam. For rods, the induced thermal lens is often accompanied by spherical aberrations, besides strong and pump-dependent defocusing. Furthermore, the depolarization of the laser beam can easily reach 20 %. In slabs, thermal lensing can be strongly astigmatic with severe aberrations, depending on the pump light distribution. If pumped longitudinally, both geometries require the pump light to be squeezed through a small aperture, leading to a very high pump intensity and an inhomogeneous pump light distribution. For transversely pumped geometries, the overlap with a TEM_{00} mode (highest intensity on axis) is poor.

The thin disk laser is very well suited for high power cw lasers, especially when using Ytterbium as laser ac-

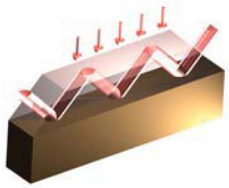

Figure 2. Zigzag slab laser schematic

tive ion. For a space-based 1064-nm Neodymium laser with high energy storage, the geometry is rather disadvantageous, mainly due to the small pumped volume and the complex pump beam shaping. Furhermore, spontaneously emitted photons at 1064 nm are not reabsorbed in Neodymium, so that the risk of PO is high as opposed to Yb-doped disk lasers.

The geometry most commonly used for Q-switched lasers in space is a side-pumped slab with a zigzag laser beam path [1, 2, 3, 4], as schematically shown in figure 2. The laser crystal is cooled via the lower large surface. The pump light is distributed over the upper large surface, which facilitates pump light coupling and keeps the pump intensity low. The strongest temperature gradients occur in the pump beam direction and are averaged out by the zigzag beam path. If the pump face is not entirely and homogeneously pumped, there will still be thermal lensing, at least in the planes transverse to the zigzag plane [2, 1]. Another problem to be faced concerning high energy storage is the risk of ASE and PO [5]. Due to the large angle region for TIR, many spontaneously emitted photons can take a long path through the crystal, e.g. the zigzag laser beam path. Also, the zigzag geometry will always leave some undepleted inversion that can help PO to reach the laser threshold. With side faces perpendicular to the large surfaces, one can think of many closed loop total internal reflection (TIR) resonators, since the TIR angle is usually around 50-60 degrees measured from the interface. In general, the problem with ASE and PO is aggravated by the high small signal gain, which is due to the long laser beam path through the crystal and the high energy storage.

2. GENERAL DESIGN

2.1. Gain medium

There are several design aspects concerning the proper choice of the gain medium. When restricting the laser wavelength to roughly one micron, only Neodymium and Ytterbium can efficiently serve as active ions. At a first glance, Ytterbium has an appealing level structure and offers very little intrinsic energy losses. However, if an efficient amplifier is to be built, the fluence of the amplified pulse should be around five times the saturation fluence of the gain medium. Otherwise, complex multi-pass amplifier geometries have to be employed in order to achieve efficient energy extraction. The saturation fluence of Yb:YAG is approximately 10 J/cm^2, so the pulse should have a fluence of about 50 J/cm^2. This fluence exceeds typical coating damage thresholds. Therefore, Ytterbium is not a suitable laser ion for a high energy pulse amplifier.

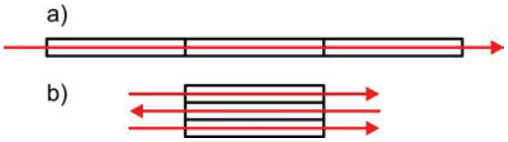

Figure 3. PO risk reduction: a) long medium, b) wide medium with triply folded beam

High pulse energy amplifiers with Nd-doped laser media have been built for decades, mainly for inertial confinement fusion experiments. Although the standard for high pulse energy amplifiers, Nd:Glass is also excluded, mainly due to its high saturation fluence and inhomogeneous level broadening. The intended laser is forced to single-frequency operation by a twisted-mode resonator. Thus, if a zigzag-type geometry is employed, naturally birefringent host materials such as YVO_4 have to be excluded. As it turns out, the best choice left over for a space-qualified amplifier is Nd:YAG. It is nevertheless a rather unsuitable medium for high efficiency operation, since roughly 36 % of the pump energy are directly lost due to nonradiative losses inside the ions. The reason why Nd:YAG is usually not used for high energy storage amplifiers is the relatively high small-signal gain. ASE and PO are strongly facilitated in high gain crystals, so measures have to be taken to prevent the onset of parasitic oscillation and to reduce ASE.

2.2. ASE and PO

To reduce the gain for a single pass of spontaneously emitted photons, the laser beam is folded three times, as shown by the crystal footprint in figure 3. The longest path through the medium is then given by the diagonal, assuming that TIR at the sidefaces is prohibited. When keeping the footprint area constant, the diagonal scales with $\sqrt{x + 1/x}$, with x as aspect ratio of the rectangle. The pathlength therefore minimizes for a square footprint ($x = 1$). It is important to note, that this reduction of ASE works only if all three beams are blocked by the Q-switch.

Another important aspect is gain that can not be accessed by the laser mode and therefore helps ASE and PO. This

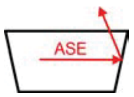

Figure 4. Outward directed trapezoid

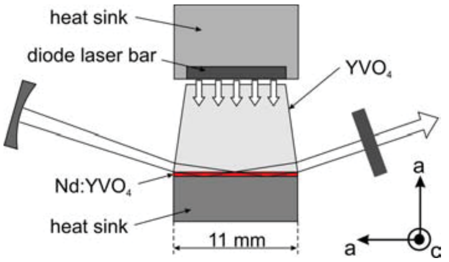

Figure 5. Topview of the CTSL

problem can be overcome by doing just a single ”zig”, a laser geometry that is commonly referred to as ”grazing-incidence” laser (GISL). Figure 5 shows the CTSL (composite thin slab laser) developed by the University of Applied Sciences Muenster [6, 7]. It consists of a thin Nd:YVO$_4$ plate diffusion-bonded to an undoped YVO$_4$ crystal. With this geometry, the only inversion left over is in the tips at the crystal edges.

Other than using the introverted trapezoid of figure 5, all side faces should form an outwards directed trapezoid, as shown in figure 4. This geometry prevents ASE from doing a multiple-bounce path along the crystal by reflecting the photons upwards into an undoped crystal.

2.3. Pumping and cooling

According to the requirements above, some general design drivers can be developed. Starting from a zigzag slab design, first of all the cooling principle of thin disk lasers is implemented. Therefore, the crystal is divided into two crystals, a thin Nd:YAG slab and a large undoped YAG crystal, which are bonded together. With the thin disk directly cooled over the large surface, heat extraction will be facilitated and transverse thermal gradients will be reduced. The undoped crystal will prevent the thin disk from bending upwards. A prototype for a laser design including all design aspects made so far is shown in figure 6. The pump light is coupled in over the large top surface. The geometry allows to use diode stacks without any pump beam shaping optics, since the pump light is TIR-guided inside the bulk undoped crystal. A highly reflective coating at the bottom side of the crystal assures a double pass of the pump light.

However, due to the thin doped crystal, the laser becomes sensitive for wavelength drifts of the pump diodes. In order to get an estimate of the percentage of absorbed pump power, a 4-nm (90 % power content) diode bar spectrum is numerically folded with a Nd:YAG absorption spectrum. The peak absorption coefficient of the Nd:YAG spectrum is conservatively assumed to be 9.5 cm^{-1}. Figure 7 shows that an 8 mm thick crystal is required to achieve more than 80 % pump power absorption, when diode wavelength drifts of 5 nm are allowed. With a 2 mm thick crystal, an effective thickness of 8 mm can be achieved by a 4-pass pumping scheme, as depicted in figure 8(a). To pump the crystal, one can simply put a vertical diode stack (stacked in fast-axis direction) close to the left side of the roof in figure 8(a). Up to date there is no commercial vertical stack available with more than 40-50 diode bars, while an efficient 500-mJ laser requires more than 200 diode bars. Therefore, the diodes are distributed over several stacks with 30 bars each. Since the diodes are clamped inside a metal holder as shown in figure 8(b), the fill factor would be rather low and the pump light distribution would be inhomogeneous. To solve this problem, the diode stacks can be arranged in an interleaved manner. Figure 8(c) shows a top view of the crystal roof. By coating the crystal with a pattern of AR and HR coatings, diode stacks of 30 bars each can be arranged such that the metal holders only cover the HR coated parts of the pattern. Another advantage of this pump geometry would be pump redundancy. Since the geometry is scalable, redundant stacks can be implemented to compensate for the failure of a whole diode stack. To conclude, figure 8(d) shows the complete laser crystal layout with the triply folded laser beam.

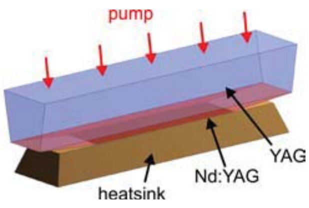

Figure 6. Laser prototype design

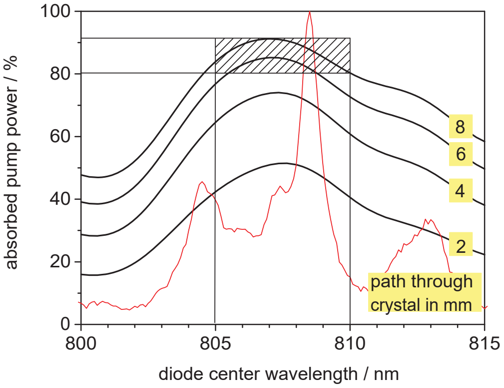

Figure 7. Effective absorption in Nd:YAG

3. MOPA CONCEPT

500 mJ of pulse energy can not be achieved with a single laser. Two simple reasons are the intracavity power and the difficulty to prevent lasing at all. Thus, a 50-mJ master-oscillator and a 450-mJ power-amplifier are used. The general laser concept is shown in figure 8.

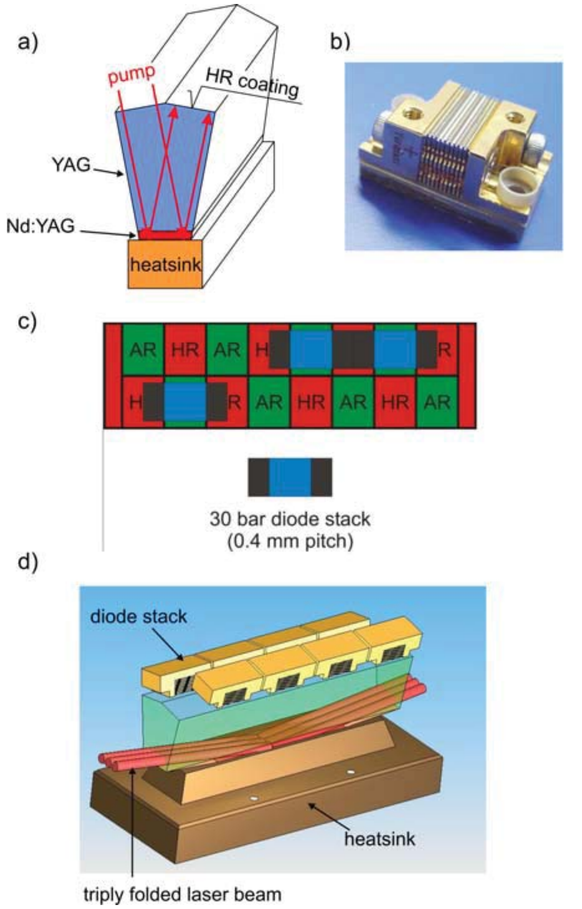

Figure 8. a) 4-pass pumping scheme, b) diode stack (DILAS), c) interleaved diode arrangement, d) complete laser concept layout

3.1. Master-oscillator

The master-oscillator is pumped by two diode stacks of 20 bars each. Using 40 bars allows to operate them at 80 % of the nominal output power, in order to compensate for unavoidable degradation. Furthermore, the pump pulse duration can be kept low to avoid excessive spontaneous emission losses.

Our numerical model based on the work of Degnan [8, 9] and Zhang [10, 11] predicts an electro-optical efficiency of about 10 % in the worst case, when roundtrip losses are assumed to be 10 %. This efficiency can only be achieved when ASE and PO are prohibited, which will be the case for our new concept. The model takes the overlap of the gain and beam intensity distribution into account. A FEM model shows that the temperature distribution is smooth and will be averaged out by the grazing-incidence laser beam path, as has been experimentally confirmed for the CTSL [6].

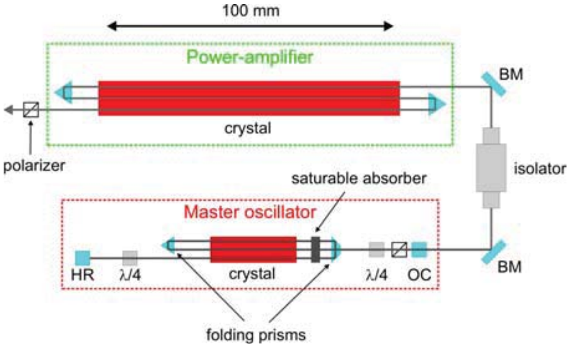

Figure 9. General MOPA scheme

3.2. Power-amplifier

The power-amplifier has to add 450 mJ to the pulse. The necessary pump energy is supplied by 8 diode stacks with 30 bars each, which are arranged in the shown interleaved pattern. Numerical calculations of the amplifier indicate an expected e-o efficiency of 14 %. Again, this enormously high efficiency can only be achieved, if ASE and PO are successfully suppressed.

4. CONCLUSION

A novel laser architecture is proposed to generate 500 mJ of pulse energy in combination with high beam quality. The main features of the concept are

- No pump beam shaping optics
- Novel 4-pass pumping scheme
- ASE and PO reduction
- Single amplifier stage
- Reduction of thermo-optical aberrations
- Scalable output energy
- Pump diode redundancy
- Derated pump diode operation for degradation compensation

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